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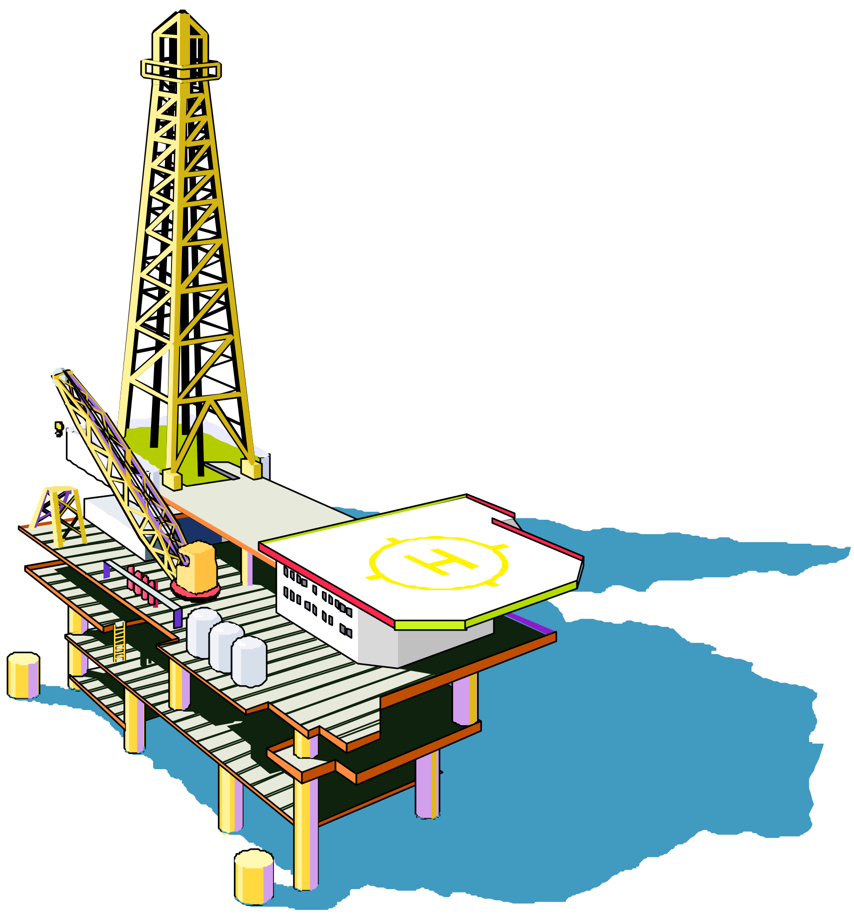
Statistical Analyses Supporting Final Effluent Limitations Guidelines and Standards for Synthetic-Based Drilling Fluids and other Non-Aqueous Drilling Fluids in the Oil and Gas Extraction Point Source Category



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1. Introduction

The summary statistics presented in this document support EPA's development of effluent limitations guidelines, standards, and best management practices (BMPs) for the control of pollutant discharges associated with the retention on cuttings (ROC) of synthetic-based drilling fluids (SBFs) and other drilling fluids that are non-dispersible in water. EPA's primary uses for these summary statistics include: (a) estimating current (baseline) pollutant discharges, (b) evaluating regulatory options, (c) calculating potential effluent limits, and (d) evaluating a criteria for accepting applications to institute BMPs.

More specifically, this document provides summary statistics for the percent retention of SBF on cuttings after treatment from each of three technology types . The technology types include shakers (with subtypes primary shakers, secondary shakers, and other shakers), cuttings dryers (with subtypes horizontal centrifuge [Mud 10], vertical centrifuge, squeeze press, and high-G dryer), and fines removal units (with subtypes decanting centrifuge and mud cleaner). These summary statistics include volume-weighted and uniformly-weighted mean retention of SBF on cuttings and their associated variances for individual wells. In addition, the arithmetic mean, variance, 95th percentile, and 99th percentile of the well means are computed, summarizing both volume-weighted well means and uniformly-weighted well means.

These analyses reflect some revisions and updates in data submitted in response to the March 2000 Notice of Data Availability. The most significant revision reflects new data submitted by industry. Another revision is that EPA accepted industry comments to use certain data quality criteria for selecting data used to develop ROC limits. EPA also added an analysis that addresses the ability of drilling fluids treatment technologies to meet ROC limits when using technologies different than those forming the technology basis of the limits. The statistical methodology for calculating potential ROC limits has not changed since the Notice of Data Availability.

2. Data Description

Industry and equipment vendor representatives provided EPA with percent retention measurements on drill cuttings discharged from solids control systems. These data were recorded as percent SBF on cuttings in a sample ([Weight of SBF]/[Weight of Wet Cuttings], expressed as a percentage). Since quantitation limits were under development for these measurement methods as the data presented here were being collected, none of the percent retention data are identified in EPA's database as being "non-detect." Associated data generally included either the drilling depth or the length of a segment drilled, pipe diameter, drilling fluid treatment technology, backup data for the calculation of percent retention, and location of the drilling site. EPA's engineering review of the raw data is documented in the memo from Lynn Petrazzuolo and Gary Petrazzuolo of Avanti Corporation to Birute Vanatta of ERG titled *Engineering Review of SBF Retention-on-Cuttings Data*, dated December 12, 2000.

EPA analyses presented in this report used both: (a) the total depth of the well at the time the associated ROC measurement was taken and (b) the length of the interval drilled since the previous ROC measurement was taken. However, data submitted to EPA either provided one or the other. To convert from total depth to drilling interval, the data were first sorted by date within each well and the length of the segment drilled was computed by taking the differences between depths for each pair of successive records. To convert from drilling interval to total depth, the data were first sorted by date within each well and all drilling intervals prior to that associated with the current ROC measurement were summed.

For purposes of analysis and the development of potential limits, treatment technology categories or subcategories are: primary shakers, secondary shakers, shakers, horizontal centrifuge (Mud 10), vertical centrifuge, squeeze press, high-G dryer, cuttings dryer 1 (a combination of the horizontal centrifuge, vertical centrifuge, squeeze press, and high-G dryer subcategories), cuttings dryer 2 (a combination of the horizontal centrifuge, vertical centrifuge, and squeeze press subcategories), cuttings dryer 3 (a combination of the horizontal and vertical centrifuge subcategories), decanting centrifuge, mud cleaner, and fines removal (a combination of the decanting centrifuge and mud cleaner subcategories).

3. Statistical Methods

EPA generated summary statistics for individual measurements of retention on cuttings (ROC), uniformly weighted means for ROC, and volume weighted means for ROC. The volume used for weighting the mean is that associated with the cuttings contained within the interval drilled. We computed means and variances for percent retention of drilling fluids from individual wells in the various technology categories and subcategories described above. In addition, EPA presents means, variances, 95th percentiles, and 99th percentiles of the well means for these same technology categories or subcategories.

Note that the retention on cuttings estimates presented here have been calculated without the use of detection or quantitation limits. Data were originally reported without detection or quantitation limits because the measurement method for retention on cuttings was under development at the time. However, with the publication of this regulation, EPA is promulgating a quantitation limit (minimum level or ML) of 2%. EPA used measurements below quantitation in the development of numerical limits because the lab equipment was calibrated to the reported levels or lower and unbiased measurement results below quantitation are appropriate for use in large datasets that describe the general performance of a technology over time. EPA recognizes that such measurement results are variable but measurement results above the quantitation limit are also variable and censoring the ROC dataset with quantitation limits would deny the Agency the ability to characterize the drilling fluid treatment technologies with the most precise and unbiased measurement results available.

3.1 Data Evaluation

EPA evaluated: (1) the relationship between depth drilled and percent retention and (2) the probability distributions of individual percent retention measurements within wells, volume weighted well means, and uniformly weighted well means.

EPA's evaluation of the relationship between depth drilled and percent retention was graphical. Figures 1 - 6 graphically display the relationship between depth drilled and percent retention on cuttings by well and by technology. The six individual technologies displayed here are those considered as the bases for the development of numeric limits. These technologies are horizontal centrifuge (Mud 10), vertical centrifuge, squeeze press, high-G dryer, decanting centrifuge and mud cleaner. Figure 7 displays the relationship between depth drilled and percent retention on cuttings by technology, without regard to the individual well.

EPA's distributional evaluation was both inferential and graphical. Where the inferential Shapiro-Wilk statistic is calculated from the observed values ("X_{ij}" or "X_i" in Table 1), the probability that the data come from a normal distribution is estimated. Where the Shapiro-Wilk statistic is calculated from the log of the observed values ("*log*(X_{ij})" or "log(X_i)" in Table 1), the probability that the data come from a lognormal distribution is estimated. Selected graphical analyses (Figure 8) indicate how closely the uniformly weighted well means follow either the normal or lognormal distribution by plotting the observed probability of obtaining a particular well mean versus the probability that such a mean would have been obtained under either the normal or the lognormal distribution.

3.2 Estimation of Volume-Weighted and Uniformly-Weighted Means with Variances for Individual Wells

Table 2 presents estimates for uniformly-weighted well means and volume-weighted well means. The uniformly-weighted well means are the arithmetic mean of percent retention, whereas the volume-weighted well means are calculated under the assumption that the percent retention associated with the volume of drill cuttings (a function of pipe size and length of segment drilled) provided a more appropriate source for estimating the mean. Theoretically, smaller pipe sizes generate smaller cutting that expose more surface area to the drilling fluid. The greater surface area would lead to greater retention of SBF on cuttings.

EPA estimated volume-weighted means and variances (Sokal and Rohlf, 1969[1]) for individual wells as follows:

$$\bar{x}_i = \sum_{j=1}^{n_i} w_{ij}\, x_{ij} \Big/ \sum_{j=1}^{n_i} w_{ij}$$

$$s_i^2 = \left[\sum_{j=1}^{n_i} w_{ij}\, x_{ij}^2 - \left(\sum_{j=1}^{n_i} w_{ij}\, x_{ij} \right)^2 \right] \Big/ \left(1 - \sum w_{ij}^2\right)$$

Estimators of uniformly-weighted means and variances for individual wells are:

[1] Sokal, R. R. and F. J. Rohlf. (1969) Biometry, 3rd edition. Page 42. New York: W. H. Freeman and Company. ISBN:0-7167-2411-1.

$$\bar{x}_i = \sum_{j=1}^{n_i} x_{ij} \Big/ n_i$$

$$s_i^2 = \sum_{j=1}^{n_i} \left(x_{ij} - \bar{x}_i \right)^2 \Big/ \left(n_i - 1 \right)$$

where

w_{ij} = volume associated with the jth record from the ith well

= B * (½ * pipe diameter)^2 * (interval drilled)

x_{ij} = percent retention for the jth record from the ith well

n_i = total number of records from the ith well,

j = 1,..., n_i

i = the ith well, i = 1, ..., n

For EPA to calculate the volume of cuttings in an interval drilled, it was sometimes necessary to use records indicating that the interval drilled was either zero or negative. If the interval drilled associated with a non-missing retention measurement was zero then the retention value associated with the zero drilling interval and the retention value associated with the positively valued drilling interval from the immediately preceding record were averaged and applied to the volume weight associated with the positively valued drilling interval. If the drilling interval in the immediately preceding record also was zero, then the record for percent retention did not enter the volume-weighted retention analysis. This procedure is based on EPA's assumption that measurements associated with no new drilling will reflect characteristics of the cuttings generated during the previous drilling interval. EPA handled negative intervals drilled, indicating that the pipe was pulled up and drilling proceeded in a different direction, as zero and processed such retention values as described above.

3.3 Estimation of the Mean, Variance, and Upper Percentiles of Well Means (assuming well means are normally distributed)

Table 3 presents arithmetic means and variances of the volume-weighted or uniformly-weighted well means and upper percentiles (95th and 99th). These estimates were calculated by the following formula, assuming that both the volume-weighted and uniformly-weighted well means follow a normal distribution:

$$\bar{x} = \left[\sum_{i=1}^{n} \bar{x}_i\right] \Big/ n$$

$$s^2 = \left[\sum_{i=1}^{n} (\bar{x}_i - \bar{x})^2\right] \Big/ (n-1)$$

$$p_{95} = \bar{x} + z_{0.95} s$$

$$p_{99} = \bar{x} + z_{0.99} s$$

where

$\bar{x}_i$ = volume-weighted or uniformly-weighted mean of percent retention for the *i*th well
n = total number of wells
$z_{0.95}$ = 95th percentile from the standard normal distribution (= 1.645)
$z_{0.99}$ = 99th percentile from the standard normal distribution (= 2.326)

Such percentiles were calculated based on data selected using the factors considered in establishing final effluent limitations guidelines, standards, and best management practices. These factors included the type of drilling fluid treatment technology in use, the existence of backup data for the retention on cuttings measurements, the foreign or domestic location of the well being drilled, and the duration of the period considered for demonstrating that a well is capable of being drilled using best management practices.

3.4 Compliance Analyses

Compliance analyses that EPA presents in Tables 4 and 5 provide information on two issues. The first issue is the likelihood that any given technology will be able to comply with a potential limit without modifying the technology, operations, or maintenance of the drilling fluid treatment system. The second issue is the predictive ability of the demonstration required prior to beginning operations under best management practices (BMPs). Table 4 displays these estimates for technologies considered under numeric limit Option 1. In numeric limit Option 1, the limit is based on a weighted average of retention on cuttings measurements from both cuttings dryer and fines removal technologies. Numeric limits are calculated under the assumption that 97% of the cuttings volume discharged comes from the cuttings dryer technology and 3% of the cuttings volume discharged comes from the fines removal technology. In numeric limit Option 2, the limit is based on a discharge from a single cuttings dryer technology.

In order to estimate the likelihood that any given technology will be able to comply with a potential limit without modifying the technology, operations, or maintenance, all useable data were compared to potential limits associated with a particular combination of factors (see Tables 4 and 5). These factors included the type of drilling fluid treatment technology in use, the existence of backup data for the retention on cuttings measurements, and the foreign or domestic location of the well being drilled.

In order to estimate the predictive ability of the demonstration required prior to beginning operations under best management practices (BMPs), data from the first one third of the depth drilled using SBF were compared to potential limits associated with a particular combination of factors (see Tables 4 and 5). These results are then arrayed next to those associated with drilling the entire depth drilled using SBF.

4. Analysis

In this section, EPA discusses the results of the relationship between well depth and percent retention on cuttings, distributional, and compliance analyses.

For proposal[2], EPA accepted the industry contention and assumed that the percent retention of SBF on cuttings increased as the depth of the well being drilled increased. However, for the notice of data availability[3], EPA found that the available data did not support this assumption. With the submission of data subsequent to the notice of data availability, EPA has again examined this assumption in Figures 1 - 7. With regard to the graphics showing the relationship within individual wells (Figures 1 - 6), EPA again finds that the available data do not support the assumption that the percent retention of SBF on cuttings will systematically increase as the depth of the well being drilled increases. While the available data do suggest such a correlated relationship in some cases, there are about as many cases in the available data that suggest a relationship in the opposite direction. With regard to the graphics showing the relationship after combining all measurements on the same technology subcategory (Figure 7) , it is difficult to see any kind of a general trend that would not be overwhelmed by the variability between wells.

For proposal and again for the notice of data availability, EPA found that the data associated with individual technologies as implemented in specific countries (considered as the bases of numeric limits for retention on cuttings) were approximately normal in distribution. Again, using inferential (Table 1) and graphical (Figure 8) analytical products to support the final rule, EPA finds that the data associated with individual technologies from specific countries are approximately normal in distribution. However, in response to comments, EPA considered basing final limits on combinations of drilling fluid treatment technologies as implemented in different countries.

There are physical, engineering, and statistical reasons why EPA believes that these different datasets do not come from the same probability distribution. The physical principles and design elements of these

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[2]White, C., U.S. EPA. Memorandum to Joseph Daly, Energy Branch through Henry Kahn, Statistics Analysis Section regarding Current Performance, when using Synthetic-Based Drilling Fluids, for Primary Shakers, Secondary Shakers, and Vibrating Centrifuge and Model Limits for Percent Retention of Base Fluids on Cuttings for Secondary Shakers and Vibrating Centrifuge. January 29, 1999.

[3]EPA, *Statistical Analysis of the Percent Retention of Drilling Fluids on Cuttings after Treatment*. March 2000.

technologies are different (see the development document) and the formation drilled in Canada is claimed to be significantly harder than that found in the Gulf of Mexico. Additionally, EPA has some question as to how well the technology was implemented on the Canadian wells since this use of the technology was conducted without experienced equipment operators. Statistically, Figure 8 shows the Canadian (foreign) wells using the horizontal centrifuge to have average retention on cuttings measurements that are noticeably higher than those found in the Gulf of Mexico (USA) when the same technology is in use and that these Canadian well averages cast doubt on the assumption of a single normal probability distribution. If the data displayed in a quantile - quantile plot, such as those displayed in Figure 8, really came from the assumed distribution then the data points would be arrayed in an approximately linear fashion. Under the assumption of a normal probability distribution, where the Canadian data are plotted with the horizontal centrifuge data from the Gulf of Mexico, the Canadian data clearly do not follow the linear relationship shown with the data from the Gulf of Mexico. Where the lognormal distribution is assumed, the Canadian data arguably do follow the same linear relationship shown with the data from the Gulf of Mexico. However, the well average retention on cuttings measurements from Canada are all higher than those found in the Gulf of Mexico and that argues that the Canadian data do not belong to the same probability distribution as that associated with the data from the Gulf of Mexico. Since these technologies appear to be physically and statistically different, a single distribution for retention on cuttings from any combination of cuttings dryer technologies does not appear to exist.

The compliance analysis presented in Tables 4 and 5 are intended to display: (1) estimates of the likelihood that any given technology will be able to comply with a potential limit without modifying the technology, operations, or maintenance and (2) estimates of the predictive ability of the demonstration required prior to beginning operations under best management practices (BMPs). In general, these estimates demonstrate that there are some cases where technologies different than those that form the basis for a potential limit would be able to meet that limit. For example, the first line of Table 5 indicates that 53 wells in EPA's database would be able to meet a limit that Table 3 tells us was based on 41 wells. This means that at least 8 of the wells in EPA's database were using some technology different than the technology basis of that potential limit. These estimates also demonstrate that, although there is some increased variability due to the use of a smaller sample size, the BMP demonstration period seems to provide reasonable predictions for the well average retention on cuttings achieved when operations and maintenance are maintained throughout the drilling of the entire well.

5. Final Effluent Limits

EPA selected two final numeric limits for the retention of SBF on cuttings. For drilling fluids with the environmental properties of esters (toxicity and bio-degradation), the well-average ROC not to be exceeded is 9.4%. This is based on the uniformly weighted within well averages of measurement results from Cuttings Dryer Technology 1 that include foreign data but exclude measurement results without backup data. Again, Cuttings Dryer Technology 1 included horizontal centrifuges, vertical centrifuges, squeeze presses, and high-G dryers. For all other synthetic based drilling fluids, the well-average ROC not to be exceeded is 6.9%. This is based on the uniformly weighted within well averages of measurement results from Cuttings Dryer Technology 3 that include foreign data but exclude measurement results without backup data. Again, Cuttings Dryer Technology 3 included horizontal and vertical centrifuges. In both cases, as was proposed and presented in the notice of data availability, the numeric limit is estimated as the 95th percentile of a normal distribution for the well-averages.

Comments in response to the proposal and the notice of data availability suggested considering the following factors in the development of final numeric limits: (a) the hypothesis that retention on cuttings is related to the depth drilled, (b) documentation of data, (c)geology of areas in the US that do not currently have drilling operations, and (d) flexibility in the choice of technology used to meet final numeric limits.

With regard to factor (a) the hypothesis that retention on cuttings is related to the depth drilled, EPA rejects this hypothesis based on the analysis presented in section 4. As a consequence, final numeric limits are based on uniformly weighted well averages as opposed to volume weighted well averages.

With regard to considering factor (b) documentation of data, EPA has agreed with industry comments that numeric limits should be based on ROC data where backup data are available to describe how those measurement results were obtained. As a consequence, measurement results without backup data were excluded from the datasets used to develop final numeric limits.

With regard to considering factor (c) the geology of areas in the US that do not currently have drilling operations, EPA has provided a reasonable allowance for the increased variability expected in such locations. EPA provided this allowance by including data for wells that were not drilled in the US, as opposed to basing numeric limits on a 99th percentile. Use of the 99th percentile was discussed in the notice of data availability but including data from foreign wells directly includes variability associated with formations different than those that currently have drilling operations within the United States. Use of the 99th percentile would have been an alternative method to allow for more variability but the allowance could not be tied to the motivating source of variability, which is that due to drilling in areas in the US that do not currently have drilling operations. EPA further notes that the well average used for compliance with the ROC limit is roughly analogous to the monthly average limits EPA generally sets equal to a 95th percentile estimate. EPA generally uses 99th percentile estimates as the basis for limits set on single measurement results[4].

With regard to factor (d) providing flexibility in the choice of technology used to meet final numeric limits, EPA included several different technologies in the datasets used to develop two final numeric limits. In particular, the high-G dryer was included in the technology basis used to develop final numeric limits for drilling fluids with the environmental properties of ester based drilling fluids. This technology is particularly important because it appears to take less space than other technologies and it may fit on drilling rigs that

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[4]Kahn, H.D. and Rubin, M.B., Use of Statistical Methods in Industrial Water Pollution Control Regulations in the United States, *Environmental Monitoring and Assessment*, Volume 12, pages 129-148, 1989.

may not otherwise be able to install a cuttings dryer technology. For wells used in the development of final numeric limits, three out of six high-G dryers, all five squeeze press units, all eight vertical centrifuges, and twenty-five out of twenty-six horizontal centrifuges demonstrated their ability to comply with the numeric limit of 9.4 without further attention to operations, maintenance, or design. For all other SBF drilling fluids, the numeric limit is based on combining data from the horizontal and vertical centrifuges. Both technologies are included to provide industry the ability to choose between equipment vendors. For wells used in the development of the final numeric limits, all eight vertical centrifuges and twenty-four out of twenty-six horizontal centrifuges demonstrated their ability to comply with the numeric limit of 6.9 without further attention to operations, maintenance, or design.

As discussed in section 4, a consequence of both factors (c) and (d) is that using a normal probability distribution between wells means is a only a rough approximation to the true distribution between well means. However, in order to provide this industry with the flexibility in selection of drilling fluid treatment systems necessary to encourage the use of more environmentally benign drilling fluids, to allow for variability in drilling through formations that do not currently have drilling operations, and to follow EPA's proposed methodology for estimating percentiles, EPA based final numeric limits on combinations of drilling fluid treatment technologies from both foreign and domestic wells . Combining data from various technologies and locations does allow for the calculation of 95th percentiles based on EPA's proposed methodology. EPA's proposed methodology assumes that the well means are approximately normal in probability distribution. As proposed, EPA is establishing limits equal to 95th percentiles estimated from the performance of wells using the technology bases for ROC limits.